Comparative life cycle analysis of façade passive systems in the Mediterranean: comfort, energy, and carbon

Comparative life cycle analysis of façade passive systems in the Mediterranean: comfort, energy, and carbon

Lara Mifsud[1], Francesco Pomponi[2], Alice M. Moncaster[3]*

[1] Paul Camilleri and Associates, Valletta, VLT 1444 Malta

[2] Resource Efficient Built Environment Lab (REBEL), Edinburgh Napier University, UK

[3] School of Engineering and Innovation, The Open University, UK

* Corresponding author: f.pomponi@napier.ac.uk

Abstract

In the Mediterranean region façade shading systems are used to reduce operational energy, particularly cooling loads. However, operational savings do not necessarily translate into net energy savings unless they outweigh the embodied energy/carbon required to manufacture, install, maintain, and dispose of these systems. This study analyses two shading devices, louvers and meshes, from a whole-life perspective in Malta. We first establish, through dynamic energy modelling, the operational energy and carbon savings achieved, and results show that both louvers and meshes are capable of savings in terms of operational energy—20% to 40% compared to the base case. Secondly, we establish the embodied energy and carbon through a life cycle analysis. Although based on the limited data available for Malta, findings suggest that net energy and carbon savings are only achieved by two of the 22 configurations investigated, both mesh systems. These results highlight the urgent need to investigate shading systems to establish net energy and carbon whole-life balances. The risk is otherwise that we will save less operational energy in the future, from decarbonised energy grids, than we have already spent through a surge of embodied energy from current, carbon intensive grids, therefore exacerbating the climate crisis.

Keywords: façade passive systems; LCA; embodied energy and carbon; comparative analysis; thermal comfort.

1 Introduction

In a bid to help combat climate change, EU leaders have pledged to reduce emissions by increasing energy efficiency by 20% until 2020, by an additional 7% by 2030, and by a total of 80% by 2050 [1]. These targets are then adopted by member states and tailored to national contexts through roadmaps and milestones. Malta's Nearly-Zero Energy Building (NZEB) plan, was published in August 2015 by the Ministry for Transport and Infrastructure [2], and confirmed Malta's commitment to the NZEB targets laid out in the EU Directive on the Energy Performance of Buildings. However, by analysing the greenhouse gas (GHG) emissions caused by each European country, it is evident that Malta is still nowhere near reaching these targets [3]. For example, the energy demand in Malta increased by 3.7% in recent years, partly due to the increase in the temperatures the island experienced [4].

Reports indicate that heating and cooling in buildings account for a significant proportion of the EU's energy consumption [5]. As a result, the European Commission has launched its first plan to reduce heating and cooling through all EU countries. This strategy includes plans to make new and old buildings more energy efficient [5], in line with the Energy Performance of Buildings Directive to progress towards NZEBs [6]. One way of achieving NZEBs in warm climates is through the use of passive design strategies [7]–[9], and particularly passive cooling systems [10], [11]. Passive cooling systems are techniques that enable to achieve comfortable indoor environments (in terms of temperature, humidity, daylighting etc.) through the use of natural energy sources [12], [13] such as wind and sun. In hot Mediterranean countries such as Malta, cooling buildings passively is still a challenge. Architects and engineers incorporate passive shading systems, such as louvers and meshes, in building façades to try to reduce the cooling loads. These cooling loads form part of the building's operational energy (OE) demand and GHG emissions (so called operational carbon, OC) which are related to the building use phase [14]. To date, however, it is still unclear if the OE&C savings these systems achieve outweigh the embodied energy (EE) and carbon (EC) associated with them. EE&C is defined as the cumulative energy demand (EE) and GHGs emitted (EC) during all stages of a material's life cycle. Such stages include, material extraction, production, transportation, on-site construction, demolition and disposal [15]–[17].

Most existing research related to façade studies lacks a holistic approach, especially for warm climates such as the Mediterranean one. This study will address this gap and aims to establish holistically the performance of such shading systems (louvers and meshes). This is achieved through comparative comfort analysis to ensure they meet the intended primary function, dynamic energy modelling to quantify the saving potential in warm climates, and life cycle assessment (LCA) to establish whether the operational energy savings linked to these systems do translate into net savings from a whole-life perspective.

2 Previous works

This section reviews existing literature on both shading devices as passive cooling systems and their life cycle environmental performance falling within the scope of this article. Each area is addressed in turn in the sub-sections that follow.

2.1 Shading devices as passive cooling strategies

Passive shading devices are used to reduce solar gains, and hence cooling loads, in buildings. Shading devices greatly influence the interior environment and the user's perception of, and interaction with, the space [18]. Freewan [19] recommends key parameters which one should consider whilst designing such systems. However, for louvers and other shading systems alike, there are other factors which have to be regarded if these devices are to perform successfully and reduce internal temperatures. For instance, effective louver systems are dependent on correct orientation, the inclination angle of the louver and finally the louver size in relation to the glazed area [20], and none of these are part of the key parameters recommended by Freewan [19].

Alzoubi and Al-Zoubi [21] compared vertical and horizontal shading devices installed on south façades in Jordan. Their simulation found that for vertical louvers, higher illuminance levels were achieved with lower heat gains. However, associated glare was not investigated and being on the South façade, horizontal louvers might perform better in eliminating direct sunlight, hence reducing glare. This could influence greatly the user's interaction with the designed space. Palmero-Marrero and Oliveira [20] also investigated two layouts of louvers: horizontal louvers for the east and west façades and horizontal louvers laid as a canopy for the south façade. This configuration was simulated in five different cities with increasing latitudes, ranging from Mexico to London. For the south façade the angle of inclination was the same as the respective latitude whilst for the East façade, the angle changed from 20° to 60°. A 20° inclination angle was found to be beneficial in all climates, since, with a higher angle, the cooling loads increased. However, the same thermostatic control was used for all climates, which can be disputed since the adaptive comfort approach suggests that the thermal comfort threshold is dependent on the surrounding climate [22]. Despite the lack of climatic-specific design, their research suggests that energy savings related to lower solar gains occur nonetheless.

The effectiveness of meshes as shading devices depends on their geometry, texture, the material's spectral light transmission and its reflective properties [23]. Three mesh opening ratios were simulated by Mainini et al. [24] for Milan, Rome and Palermo. A mesh opening of 60% when used with a low-g glass led to a maximum reduction of cooling loads of 40%. Furthermore, the use of such a mesh reduced the perceived radiant temperature by 3-4 °C. Mainini et al. [23] then conducted a study to assess the total primary energy used for heating, cooling and lighting for meshes with different geometries. A decrease in the total primary energy required was noted when the ratio of thickness of strand and pitch was greater than 0.4. The lowest total primary energy was reported when the thickness and pitch were equal, for the south facing façades in both Milan and Palermo. These shading systems were then compared to a venetian blind system, and it was found that cooling loads were lower for the venetian blinds, whilst lighting loads were higher. Therefore, the use of a wide spaced mesh resulted in a low energy requirement whilst still maintaining a good outside view, a factor which is sacrificed with the use of venetian blinds. Appelfeld et al. [25] also concluded that a micro structural perforated shading screen provided similar shading results to venetian blinds, with the added advantage that the view to the outside was not compromised. Sherif et al. [26], investigated external perforated window solar screens by changing the perforation percentage and depth of these screens in order to identify the optimum configurations for different orientations. They found energy savings of up to 30%. However, in all these studies, the shading system was not compared to another louver system where the louvers are more widely spaced, allowing a better visual connection to the outside.

Finally, a number of horizontal louvers and meshes were analysed by Hoffmann and Lee [27] to establish how the respective energy use intensity changes and how the latter is influenced by glare. A 12-storey office building was simulated in two climates, Houston and Chicago. Discomfort glare was reported as an issue in a 'specific metal mesh' and a polymer mesh, whilst only slight glare issues were reported for a stainless steel roller shade. When glare control was simulated, significant increases in energy required for heating and cooling purposes was noted for the mesh system. However, the glare control simulated was an interior shade, which was lowered when the discomfort glare increased significantly. This was then modelled to remain in use for the entire day. The validity of this assumption could be argued when modelled for the East façades. The latter normally experience glare early on in the day and is rarely an issue in late mornings and afternoons, therefore heating and cooling loads could have increased unnecessarily. Hammad and Abu-Hijeh [28] investigated dynamic external louvers for an office building in the United Arab Emirates, showing potential energy savings in the range of 30-34%.

Despite convincing evidence in the existing literature that passive shading systems yield operational energy savings in warm climates, there is still a lack of a comparative understanding of the performance of louvers and meshes, from both a comfort as well as an operational energy perspective.

2.2 Life Cycle Assessment of passive cooling strategies

Although traditionally operational energy represented a major share of a building's whole life energy, there is growing and convincing evidence that suggests a more balanced share of operational and embodied energy in a building's life cycle [29]. Urgent attention is also required on embodied carbon [30], [31], and the methodological challenges and data issues that embodied carbon calculations pose [32], [33]. One example of such issues is the global use of the Inventory of Carbon and Energy (ICE) database despite it being UK focused. However, there might be cases where no better data exists and primary data collection is not viable. If the ICE database is to be used, it would be important to investigate as a minimum if manufacturing processes and energy mix are similar between the UK and the country under consideration [34]. If manufacturing processes are substantially similar but the energy mix is not, a potential solution—which however certainly introduces further uncertainty on the data—is to convert embodied energy into embodied carbon by analysing the energy mix of the country under study. This was the approach followed in this article based on the energy mix for Malta. Inevitably, this represents a limitation that adds uncertainty to the results but no better representative data for Malta could be found.

In all the studies discussed in the previous section, the respective authors only investigated cooling/heating or lighting loads, which form part of the building's OE. They neglected other parts of the shading devices' life cycle that may also contribute significantly to the total energy used. In the context of façade passive systems, this means that in spite of the fact that shading devices often achieve some reduction on the cooling demand, their life cycle energy is seldom considered. Therefore, a more holistic approach is necessary to establish whether the energy and carbon they save outweighs their embodied energy and carbon related to all other life cycle stages. BS EN15978:2011 [35] defines four main stages in a building's life cycle (Figure 1). In the studies reviewed in the previous section, the only stage considered is B6 – operational energy use: it is immediately evident that significant shares of the passive system's life cycle are wholly neglected and, therefore, how inevitably partial the conclusions from those studies are.

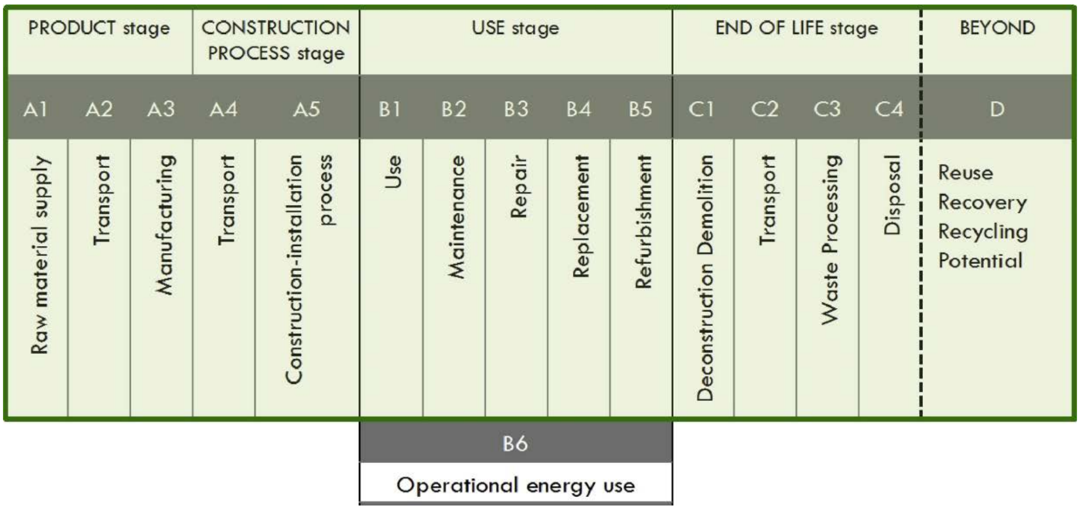


Figure 1: Lifecycle stages of a building assessment [35]

An LCA is defined as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [36]. Through an LCA, for instance, one may assess the phases that provide the highest environmental impacts and attempt to improve accordingly [37].

Huang et al. [38] carried out an LCA on different shading options in Hong Kong and found that due to the need to withstand typhoons, the EC emissions increased significantly due to larger quantities of carbon intensive materials. Stazi et al. [39] monitored the performance of, and conducted and LCA on, wooden and aluminium louvers and screens onto a window with no shading devices in Ancona, Italy. However, since these louvers were very narrowly spaced (*persiana*), most natural lighting was blocked off, thus increasing the amount of artificial light required. This increased OE significantly and surpassed the reduced heating and cooling loads required. Additionally, significant increases in embodied (non-renewable) energy were observed due to the industrial manufacturing of aluminium. Embodied energy increases were less severe in the case of the wooden *persiana*.

Babaizadeh et al. [40] carried out a cradle to grave life cycle study on five different external window-shading types, four of which were in the shape of horizontal overhangs. Three materials were analysed and these were aluminium, wood and PVC. The lowest environmental impacts were obtained for wood, followed by aluminium and PVC. However, it seems that maintenance was not considered, which might increase the environmental impacts for wood. Their reference study period is 40 years, which further strengthens the need for maintenance. The authors concluded that the use of shadings did reduce the total energy consumption for buildings over their life cycles. However, if energy figures show savings in the range of 6.42 – 8.44 x 10^5 MJ (depending on the specific system considered), carbon dioxide equivalent emissions actually increase by the same order of magnitude (3.36 – 8.86 x 10^5 $kgCO_2eq$). The same happens (i.e. an increase, which means damage) across all other impact categories analysed (e.g. acidification and eutrophication, water consumption, damage to human health and ecological toxicity, etc.).

The studies reviewed in this section show that information on the life cycle performance of façade shading systems is limited and scattered: multiple different designs for shadings are tested which makes them difficult to compare; results depend greatly on climate zones with little possibility of generalisation; and most of the existing works investigate comfort issues with energy-related implications (such as cooling or lighting) or operational energy savings in general with little to no focus on embodied energy. Therefore, this article will address some of these issues by a detailed comparison of different typical designs for Mediterranean climates, considering both the impact on the internal environment (comfort and cooling) as well as the whole life (operational and embodied) savings and costs for both energy and carbon.

3 Research design and methods

The research in this paper initially stemmed from a real-life project that one of the authors was involved in. As a result, though different research methods were used throughout, this study is primarily rooted in a case study approach [41], which is very common in built environment research [42]. Two buildings, one built and one as-yet-built, were analysed, both of which are located in the University of Malta campus in Msida, Malta. The first building, referred to as base case in the rest of the manuscript, is the recently completed Faculty of ICT, designed by TBA Periti (Figure 2 - top). This building is centred on a large open courtyard where a fully glazed curtain walling system was used for the façades. This façade has a retractable horizontal louver system installed, which can be raised or lowered according to the users' demands. The second building is a new envisaged building, called the Sustainable Living Complex (SLC). This is a new complex that will house the Faculty for the Built Environment, the faculty of Education and several other institutes. The whole complex may be split into three main parts, the lecture rooms, the laboratories/studios and the offices. The two office blocks were designed as individual buildings connected on each floor. The primary difference between the two is that one is centred round an enclosed atrium whilst the other is designed with a central open courtyard. The façades of these offices are also proposed to be fully glazed curtain wall systems with different shading treatments incorporated for different façade orientations. Both louvers and meshes were integrated into the South façades (Figure 2 - bottom) with the scope of comparing the two systems once the project is built. The different shading systems used in the SLC building are analysed in terms of thermal comfort, operational energy and carbon (OE&C) and embodied energy and carbon (EE&C). The other system installed on the ICT building was used as the benchmark for comparisons against the other systems considered.

Figure 2: The faculty of ICT (top) and the South façade of one of the office blocks of the SLC (bottom) - Team Two Architects.

3.1 Assessed Scenarios and Configurations Considered

The functional unit of this study is a 1.5 m (W) x 3.75 m (H) portion of the South façade, with an openable area of 30%. The offices oriented towards the South façade were modelled, since such façades normally experience the highest heat gains. The height of this unit is based on the floor-to-floor height for this office block. This façade is made up of two main elements: the glazed system and the shading system.

3.1.1 The glazed system

This system is based on the façade installed in the ICT building in the University of Malta campus. This is a double glazed system with argon gas with a total U-value of 1.1 W/m^{2}K. However, this sort of system is permanently closed, and so does not allow any sort of natural ventilation to take place. The building envelope envisaged for the SLC will instead be openable. Therefore, the system modelled in this study allows the glazed windows to open through a sliding mechanism.

3.1.2 The shading systems

Five different shading systems were investigated in this study including three louver and two mesh systems. For the louver and mesh systems considered, the distance between each shading system and the glazed façade was assumed to be 150 mm. Louver System 1 (LS1) consists of horizontal louvers with a length of 500 mm, a pitch of 750 mm and angled at 20° (Figure 3, left), whereas Louver System 2 (LS2) consists of horizontal louvers with a length of 250 mm, a pitch of 400 mm and angled at 15° (Figure 3, right).

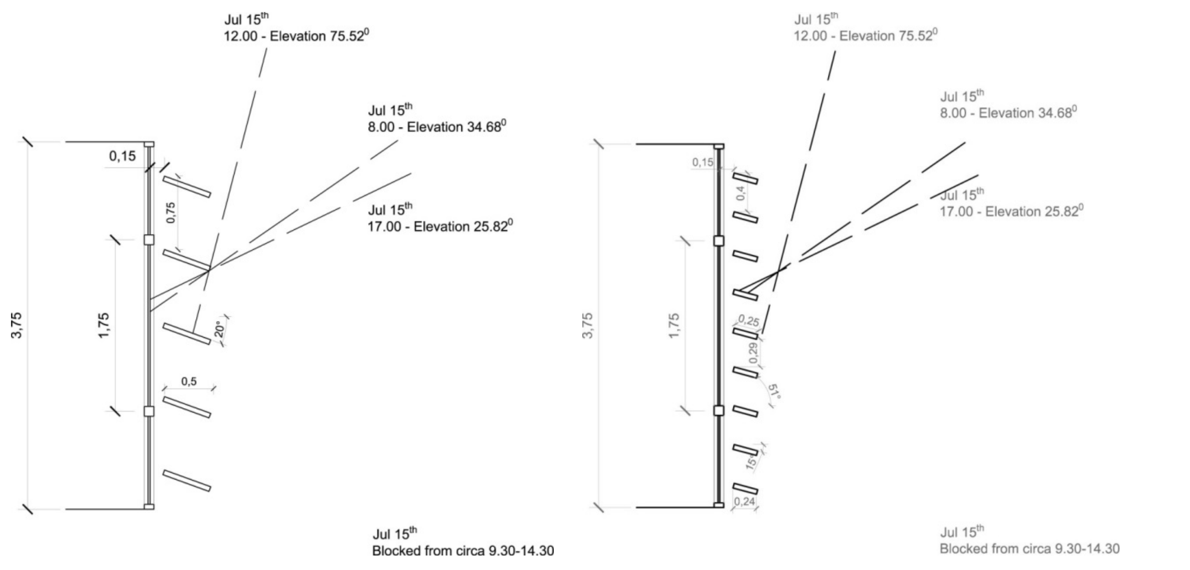


Figure 3: Louver system 1 [left] and Louver system 2 [right]

In both systems considered so far, when the sun's angle of elevation is greater than 50° and 51° respectively, direct sun is obstructed. The Louver System 3 (LS3) is based on the system currently installed in the Faculty of ICT (Figure 4). These are narrow retractable external louvers which are controlled by the individual users.

Figure 4: The façade of ICT with retractable external louvers (left), and the retractable louver system (right) (Schüco International, 2016).

As for the mesh systems, the Mesh System 1 (MS1) is a wire mesh with an open area of 51%. The wire mesh forms square openings of circa 5 mm (Figure 5, left). The second mesh type is also a wire mesh, however, with an open area of 25%. This mesh is woven from flat wires with square openings of circa 10 mm (Figure 5, right). This mesh was chosen as the opening ratio is in line with the window to wall ratio recommended by American codes [43].

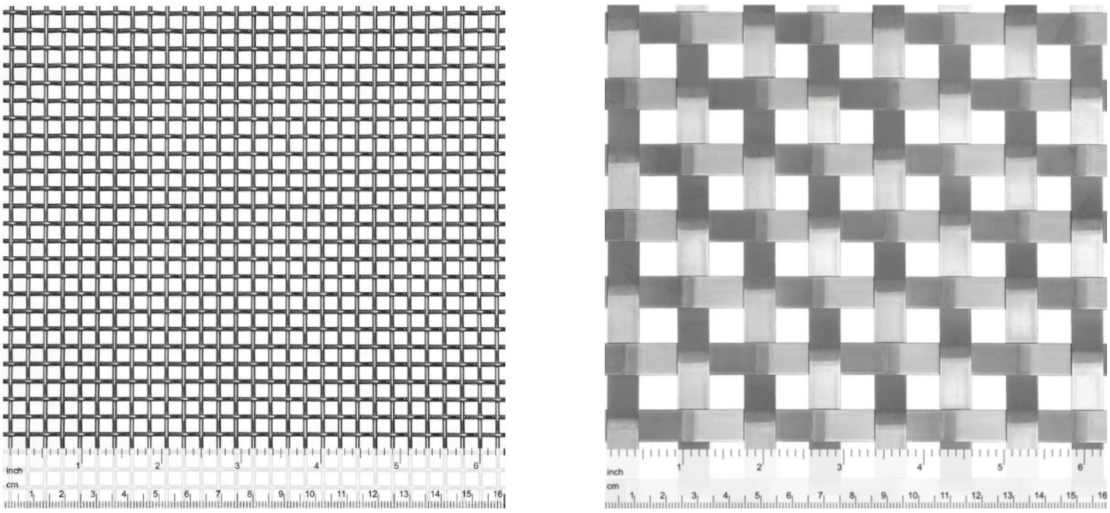


Figure 5: Mesh system 1 **[44]** *(left), and Mesh system 2* **[45]** *(right)*

3.2 Thermal Simulation

A thermal simulation of the buildings on IES-VE was carried out to establish the OE&C required to provide a thermally comfortable environment. In order to avoid the results being influenced by other architectural features used in the SLC, such as the atrium effect, only a part of the office block was modelled. This is a simplification since the architectural feature of the atrium is likely to play a role in the overall energy balance of a building. However, our focus was to investigate the potential for louvers and meshes in the context of Malta, and therefore we have chosen to limit our simulation to the more standard office part of the building to increase the generalisability of our findings. This is shown in Figure 6. The construction materials assigned in the model for the generic elements, such as floors, walls and ceilings were derived from the materials specified in the project plans and used in the building construction. The simulation, with exactly the same conditions, was repeated with each respective shading system modelled onto the glazed façade.

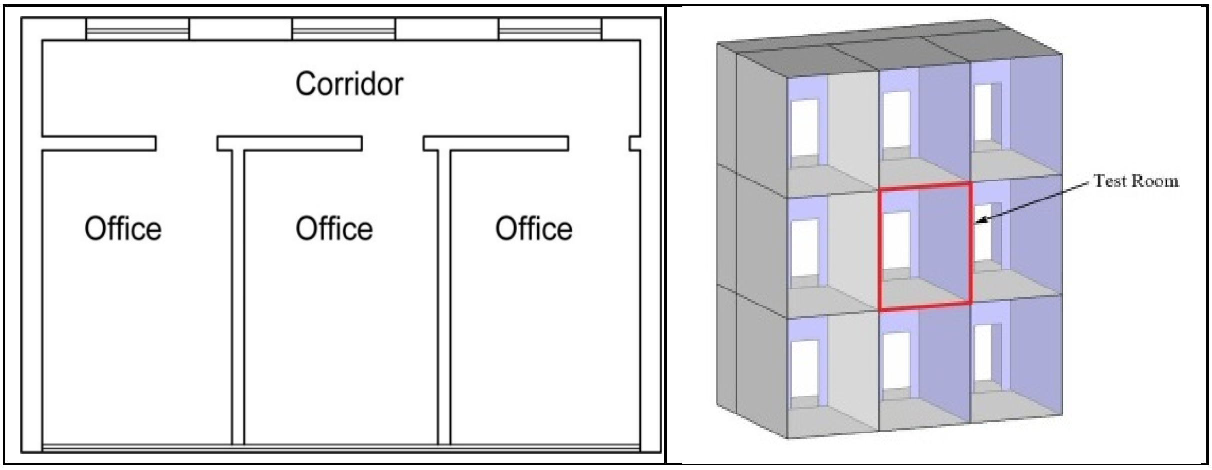


Figure 6: Part of the office block which was modelled (Author's own), plan (left) and axonometric view (right)

The louver systems, LS1 and LS2 were simulated as external louvers with the proposed geometry (Figure 7). The louvers of LS3 were simulated as external louvers which were lowered when the solar radiation exceeded 400 W/m^2. This value was obtained after analysing the building without any sort of shading devices and establishing the lowest solar radiation which caused an uncomfortable indoor environment. It is also in line with similar values (e.g. 300 W/m^2) [14], [46] which were used in colder climates, therefore justifying a higher one for Malta. The model was then simulated to include retractable, external louvers when the solar radiation on the glazed façades reached that level, for the operational hours. The operational hours assumed for this simulation were from 8:00-18:00 hours daily.

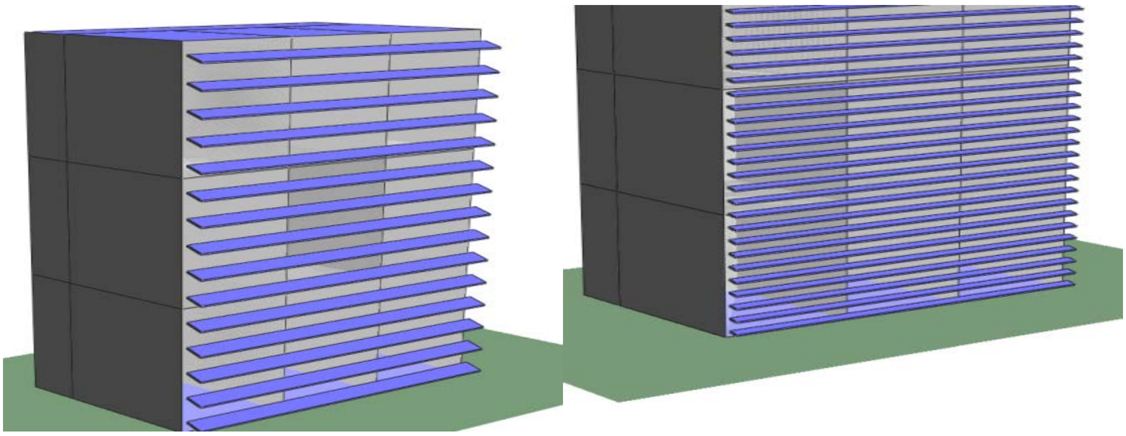


Figure 7: The louver systems modelled: LS1 (left), and LS2 (right) (Author's own)

A sensitivity analysis was carried out to identify the best way to model a mesh in the simulation software used, and to find a compromise between simulation time and accuracy. Therefore, an actual mesh was simulated and compared to a vertical plane with the same opening percentage. These were both modelled as rooms directly linked to the actual building. The side elevations of these rooms were modelled as windows which were open throughout the whole simulation. For the actual mesh, the openings were also modelled as windows which were fully opened throughout. The temperature found within each respective room was then compared and analysed. The temperature difference was noted to be 1.7% at worst. This difference was deemed to be negligible allowing the mesh shading systems to be modelled as a single vertical plane with the opening ratio matching each respective mesh.

Using the local weather file provided by the Institute for Sustainable Energy of the University of Malta, the running mean external temperature according to EN15251 [47] was calculated. The allowable comfortable temperature range was then calculated using the comfort assessment methodology TM52 by the Chartered Institution of Building Services Engineers (CIBSE) [48] for each month. Using this information, two types of ventilation modes were modelled in IES, the Natural Ventilation Mode (i.e. air movement in the indoor spaces is achieved without the aid of mechanical means, and solely by opening and changes of wind and air pressure linked to main wind directions, as well as windward and leeward sides of the building) and the Mixed Ventilation Mode (i.e. air movement is supported also by mechanical means). For both cases, the simulations were run solely for the months of May to September. These months were chosen to correspond with the cooling season as considered by TM52. The natural ventilation mode was modelled to allow the windows to open as the internal temperature reached 20 °C with a single condition: the windows opened provided that the outside temperature was lower than the maximum comfortable temperature as calculated for each respective month. For the mixed mode system, the windows opened when the internal temperature was within the acceptable comfortable temperature range. Once the internal temperature exceeded 24 °C, then the cooling mode was switched on. Cooling was modelled in IES VE through an Apache System handling auxiliary ventilation air exchanges required to provide the specified fresh air supply. Cooling was set to the operating temperature of 24 °C as specified by TM52. A fresh air supply rate of 10 l/s per capita as recommended by CIBSE Application Manual 10 – Natural Ventilation in Non-domestic buildings [49] was included, and this was also factored in in the resulting operational energy demand. The thermal comfort performance of each shading system considered was then investigated by using the comfort assessment methodology as specified in TM52 and the Predicted Mean Vote (PMV) comfort scale [48].

3.3 Life Cycle Assessment

A full life cycle assessment was then conducted for each shading system investigated so as to establish the whole life energy and carbon. The glazing system was ignored since this was assumed to act separately from the shading system. Two main material types were considered for each respective shading system. These were stainless steel and aluminium since both materials are very common in such systems due to their durability, strength and aesthetic qualities. Furthermore, this assumption is consistent with previous studies on the topic which consider the very same materials [23], [24], [27], [50]. For all the shading systems the mass was derived by calculating the volume of each system. The supports of each system were also taken into consideration. This life cycle assessment was developed for a single period of 25 years, which represents the expected service life of the louvers and mesh systems analysed. From the stages listed in BS EN 15978:2011 [35], the following stages were considered:

- Raw material supply, transport and manufacturing (A1-A3)
- Transport to construction site (A4)
- Operational Energy Use scenario (B6)
- Replacement scenario (B4)
- Transport to recycling plant (C2)

The rationale behind choosing the stages above is to adopt a conservative approach in light of the scope of this research. For instance, impacts related to the end of life will happen 25 years from now, and be characterised by significant uncertainty. They could be higher or lower than the impacts from construction, depending on the modelling choices and assumptions that we would have to make. This is further supported by recent work investigating the variability of embodied carbon multipliers for various life cycle stages [33]. Moncaster et al. [33] found that previous estimates of impacts from whole buildings for the end of life stages could range between 0.3 kg CO_{2eq}/kg_{MAT} to 212 kg CO_{2eq}/kg_{MAT}, depending on assumptions made. Pomponi et al. [14], [51] in studies focused on glazed façades found that impacts occurring at the end of life would be characterised by negative values (approx. -30 / -90 kg CO_{2eq}, if stage D from Fig. 1 is considered) due to the recycling potential of metals and glass. These numbers are so far apart that picking one has very little likelihood of representing any real future scenario. For these reasons, apart from the rather certain assumption of transporting materials from the building site to recycling and waste-processing plants, other end of life stages have been excluded to ensure our results would be solidly built on available evidence and broadly unaffected by modelling choices of future events.

Product Stage (A1-A3)

The data used for the Product stage was obtained from the ICE database [17]. Despite its limitations discussed in the literature review, given the scope and system boundary of this research it felt the data was sufficiently representative of the context being examined. This is because we limited our use of the ICE database to the embodied energy data, which covers established manufacturing approaches for the standard building materials assessed in this research. From the data available on embodied energy, the minimum and maximum values for the embodied carbon were then calculated through a conversion factor representative of the Maltese context. Therefore, the minimum and maximum EE and EC values were established.

Transport to construction site (A4)

The journey distance from the respective manufacturer was calculated from a web mapping service application and the shortest distance was established. By using the DEFRA [52] conversion factors the EC was calculated. By establishing the mass of fuel required the calorific value was calculated from the DEFRA guidelines, establishing an estimation of the EE. However, a limitation of this method is that the calorific value does not necessarily account for the efficiency of the engine, nor it represents the engines of the future (stage C2). Therefore, the embodied energy might be underestimated in the former case and overestimated in the latter. However, overweighting future impacts and underweighting current ones represents a conservative hypothesis given the aim of this research.

Construction and installation (A5)

Construction and installation data are few and far between. Moncaster et al. [33] reported estimated values in the range 0.000325 - 0.021 $kgCO_2/kg_{MAT}$. The upper and lower bounds are two orders of magnitude apart and picking a value in the range would be left almost to chance alone. Additionally, the EC coefficients are referred to mass units and both the louvers and the meshes are quite lightweight by design. For these reasons, A5 was excluded by our analysis. Again, in light of the scope of this work, this is a conservative hypothesis since in fact A5 would account for a probably small but certainly positive contribution to the whole life embodied carbon.

Operational Energy Use Scenario (B6)

The OE and OC required for cooling in the mixed-mode system were calculated for each shading typology through IES-VE. IES-VE can simulate the cooling loads and energy used by the building. For energy figures to be accurate, exact details of many elements (e.g., MEP, etc.) should be known. These may vary greatly from building to building and the use of loads seemed more appropriate to increase the usability of the research. The software can also simulate the carbon emissions associated with the system used for the building modelled. By knowing the cooling loads required per room, the related carbon emissions were then calculated proportionately for the functional unit in the test room of the model. Data to convert energy into carbon was taken from the International Energy Agency [53] statistics available for Malta based on the country’s energy mix and carbon emissions.

Replacement Scenario (B4)

The replacement value of the louver and mesh systems was taken as 25 years, other than the replacement value for LS3 which was assumed to be 5 years, as obtained from data from the estates manager and their experience with such systems as installed in the ICT building.

Transport to recycling plant (C2)

Due to the material selection of these systems, it was assumed that they would be transported to a recycling plant once they reach their end of life. Transportation distances were assumed based on the average distances of recycling plants from construction sites. Carbon coefficients for transports were determined as explained already for the stage A4.

3.4 Overview of Configurations Assessed

Table 1 shows all the twenty-two configurations considered in this study. Furthermore, it denotes the abbreviations listed for each typology for ease of reference to the reader.

Table 1: Configurations modelled and assessed for this research and their respective codes

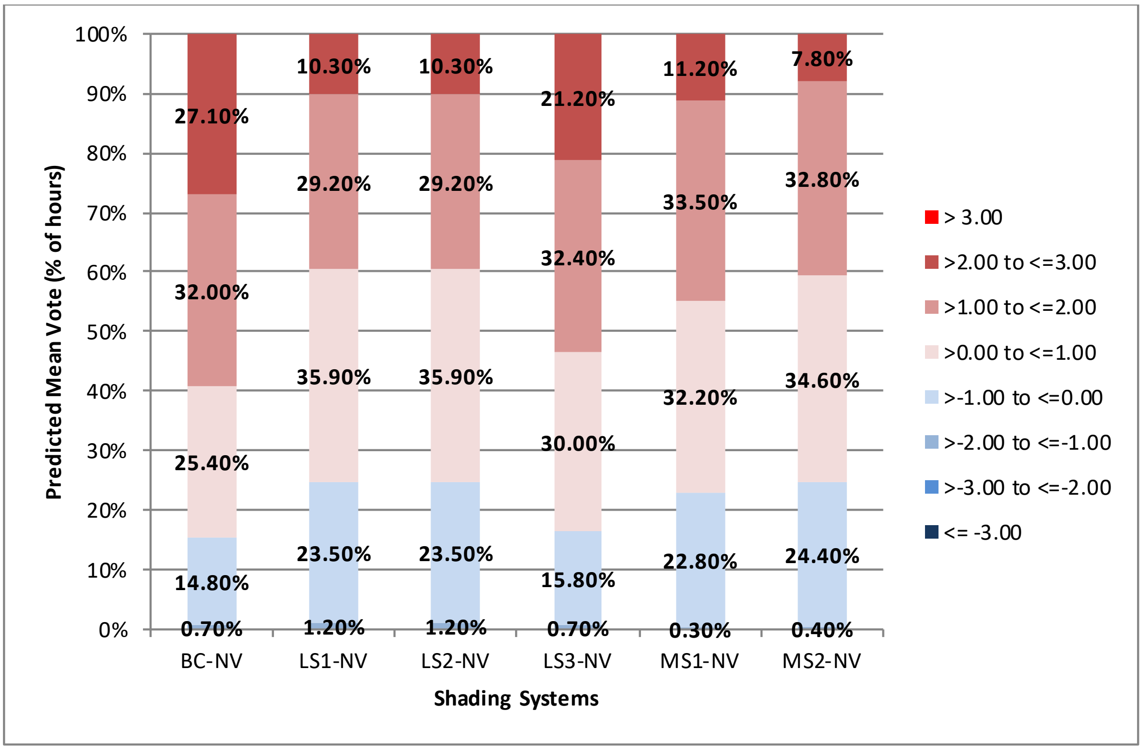
	Natural Ventilation (NV) Mode		**Mixed Mode (MM)**	
Base Case (BC)	BC-NV		BC-MM	
	Aluminium	*Steel*	*Aluminium*	*Steel*
Louver System 1	LS1-NV-A	LS1-NV-S	LS1-MM-A	LS1-MM-S
Louver System 2	LS2-NV-A	LS2-NV-S	LS2-MM-A	LS2-MM-S
Louver System 3	LS3-NV-A	LS3-NV-S	LS3-MM-A	LS3-MM-S
Mesh System 1	MS1-NV-A	MS1-NV-S	MS1-MM-A	MS1-MM-S
Mesh System 2	MS2-NV-A	MS2-NV-S	MS2-MM-A	MS2-MM-S

4 Results

Following the same logic adopted so far in the paper, results are first presented in terms of comfort to ensure the suitability of the options assessed to provide a usable indoor space. Operational energy and carbon follows, before introducing the results for embodied energy and carbon. Operational and embodied values are then reconciled to determine the overall life cycle energy and carbon balance.

4.1 Natural ventilation strategy: indoor comfort

Figure 8 (top) shows the comfort results for the natural ventilation options in terms of PMV. From the shading systems investigated, the largest percentage of time in the neutral range (-1<PMV<1) was noted for the two louver systems, LS1 and LS2, at 59.4%. In fact, an interesting observation is that these louver systems demonstrated identical results. A possible explanation for this could be that though the louvers differed in size, they offered the same amount of shading. This performance is similar to the results reported by Datta [54].



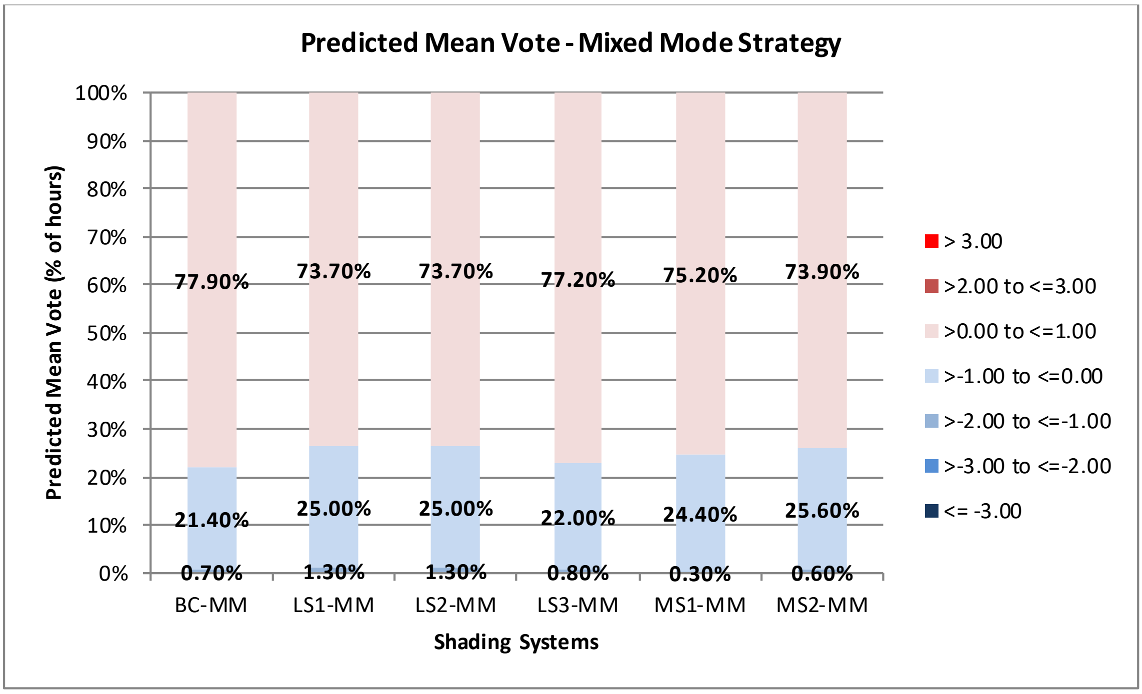


Figure 8: Predicted Mean Vote for shading systems with a natural ventilation strategy (top) and the Predicted Mean Vote for shading systems with a mixed mode strategy (bottom)

Mesh system 2 (MS2) also resulted in a comfortable region of 59%. Therefore, these results indicate that with the use of such systems, LS1, LS2 and MS2, occupants would feel comfortable nearly 60% of the occupied hours. LS1 and LS2 also resulted in the lowest overheating band where $1<PMV<2$ at 29.2%. On the other hand, MS2 reported a 32.8% in this range. These findings seem to suggest that LS1 and LS2 performed slightly better than MS2. However, it is also interesting to note that in the critical overheating band (2<PMV<3) MS2 reported 7.8%, 2.5% lower than the louver systems LS1 and LS2. This difference in these bands is significant. In fact, all rooms in LS1 and LS2 failed the TM52 comfort assessment whilst for MS2, the three rooms found at the ground floor passed. The success of MS2 could be probably due to the low open factor (25%) of the mesh, which corresponds to the recommended window to wall ratio [43].

This promising result seems to suggest that if the construction materials used for the building envelope improved, a fully functional natural ventilated building could be a possibility in warm Mediterranean climates. As expected, the highest percentage noted for the full overheating range (PMV>1) was for the base case system (BC) at 59.1%. This was closely followed by LS3 which reported an overheating range of 53.5%. This result was also anticipated considering the fact that this shading system was a retractable one controlled by the occupants. From the other shading systems investigated, this was followed by MS1 with an overheating range of 44.7%. This result can probably be attributed to the fact that MS1 was the finest mesh considered with an open area of 51%. All three systems, BC, LS3 and MS1 failed the TM52 assessment.

Given that all naturally ventilated options wholly or mostly failed the comfort assessment in their existing configurations they have been considered not to meet the primary function (i.e. providing a comfortable indoor environment) and have therefore not been investigated further.

4.2 Mixed mode strategy: indoor comfort

Figure 8 (bottom) shows the comfort results for the mixed mode options. When analysing solely the PMVs, LS1, LS2 and MS2 performed comparably with the PMVs split between the slightly warm and slightly cold region similarly. The other mesh system, MS1 resulted in a slightly higher percentage in the warmer region, with a difference of 1.3-1.5%. As expected, the BC system and LS3 reported the highest percentage in the slightly warm region. These were both noted to result in a further 2% increase from MS1. From all the shading systems considered, the louver systems, LS1 and LS2 also had the highest percentage of hours in the slightly cold/cool category where -2<PMV<-1, although the percentage is hardly of any significance overall.

4.3 Operational Energy and Carbon

The OE and OC for the configurations considered are presented in Figure 9. These values were based on the cooling loads required for each configuration assessed. By also analysing the OE&C in conjunction with the thermal comfort analysis, interesting observations may be reached. When one compares the OE required in order to obtain a thermally comfortable environment, MS2 resulted in the lowest cooling load required, 43% lower than the BC, 26% lower than LS3 and nearly 16% lower than LS1, LS2 and MS1. From the shading systems considered the highest operational energy was for LS3, which still reduced OE by 20% when compared to the BC. LS1, LS2 and MS1 all performed comparably, resulting in an OE saving of around 31%.

These results suggest that, overall, the temperatures obtained in MS2 were lower than the temperatures for the other shading systems considered, even though the PMV would have fallen within the same range. As a result, the cooling load required to obtain the target comfortable temperature for MS2 was sensibly lower, resulting in higher energy savings. A possible explanation for this performance could be due to the increased uniformity in the shading pattern obtained with a mesh system. The shading pattern obtained from horizontal louver systems is heavily dependent on the sun's angle. In fact, shading is significantly limited during the early mornings and late afternoons as the sun's angle would be lower. However, with a mesh system, since the shading fabric is vertical, and not horizontal, the solar rays are still relatively obstructed when the sun's elevation is relatively low. This explanation could also indicate why the cooling loads of MS1 were practically equal to the cooling loads obtained for the louver systems LS1 and LS2, even though the PMV results suggested that MS1 was warmer. Furthermore, LS1 and LS2 seem to indicate a larger fluctuation in the air temperature than the mesh systems due to the larger percentage of PMVs found below -2 and above 2. Another possible explanation for this behaviour could be attributed to the gap found between the glazed façade and the mesh systems. Though this gap was equal for all fixed louver and mesh systems considered, the vertical nature of the mesh could have encouraged a better air flow similar to double skin façades. Overall, these results clearly indicate the need to investigate further the use of mesh shading systems combined with glazed façades.

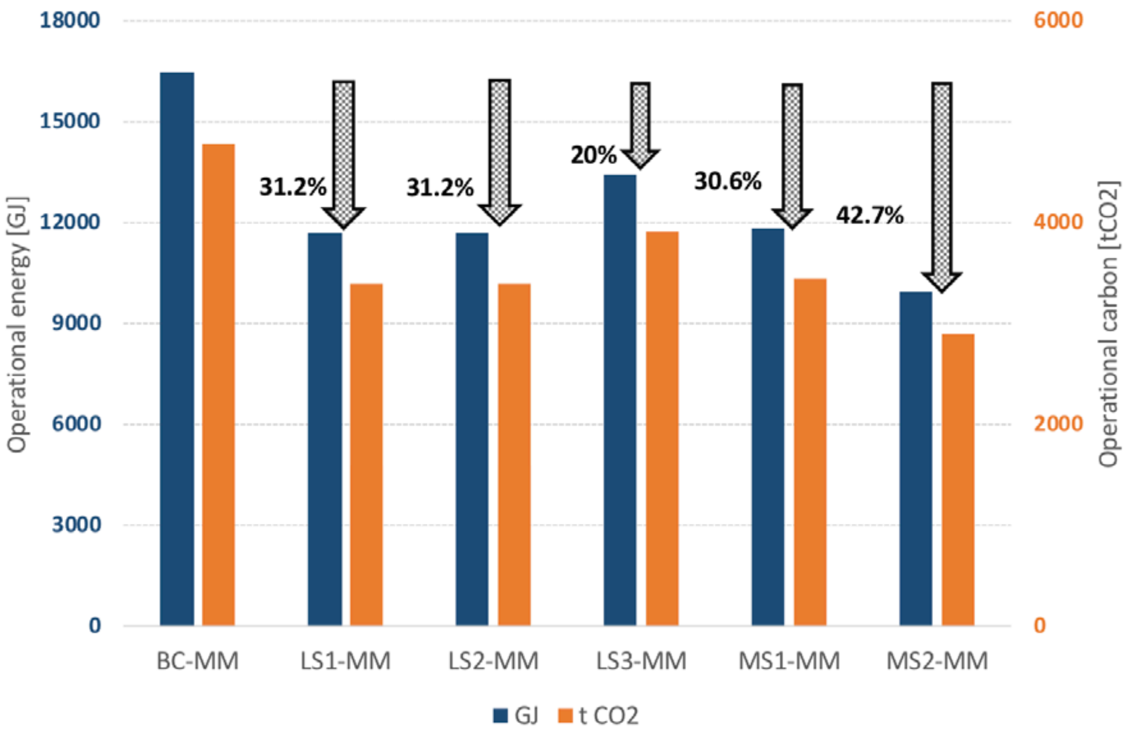


Figure 9: Operational energy and carbon required for the configurations considered

The OC results obtained for the configurations considered are presented alongside the energy values. Reductions are of course identical. As explained in the methodology section, conversion from energy to carbon was based on IEA data for the Maltese energy mix.

4.4 Embodied Energy and Embodied Carbon

Figure 10 (top) presents the average values of the embodied energy calculated for each shading system, and Figure 10 (bottom) shows the percentage that each life cycle stage represents. The highest embodied energy was noted for LS3 whilst the remaining louver systems, LS1 and LS2 performed similarly. The lowest embodied energy was noted for MS1, which was circa 36% lower than MS2. MS1 performed particularly well due to the reduced mass required, subsequently a lower EE was required during the product stage. Furthermore, when compared to the other shading systems considered, the mesh systems generated nearly 90% less EE than LS1 and LS2, and circa 94% less than LS3. Overall, aluminium systems resulted in significantly higher embodied energy impact. In fact, a percentage increase of 29% was noted across all the systems considered. This result may seem surprising especially considering that the weights of aluminium systems are significantly less than the corresponding steel systems.

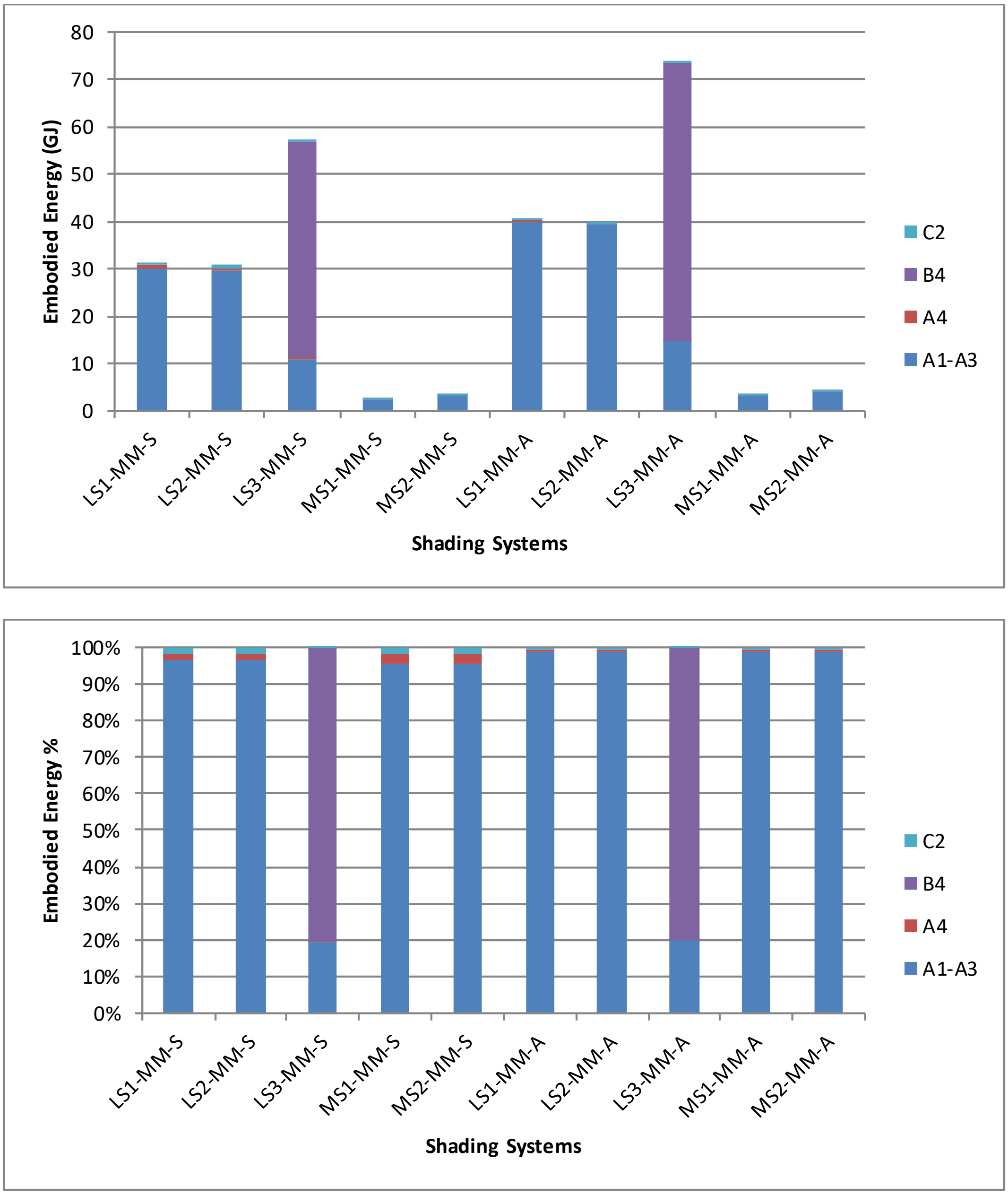
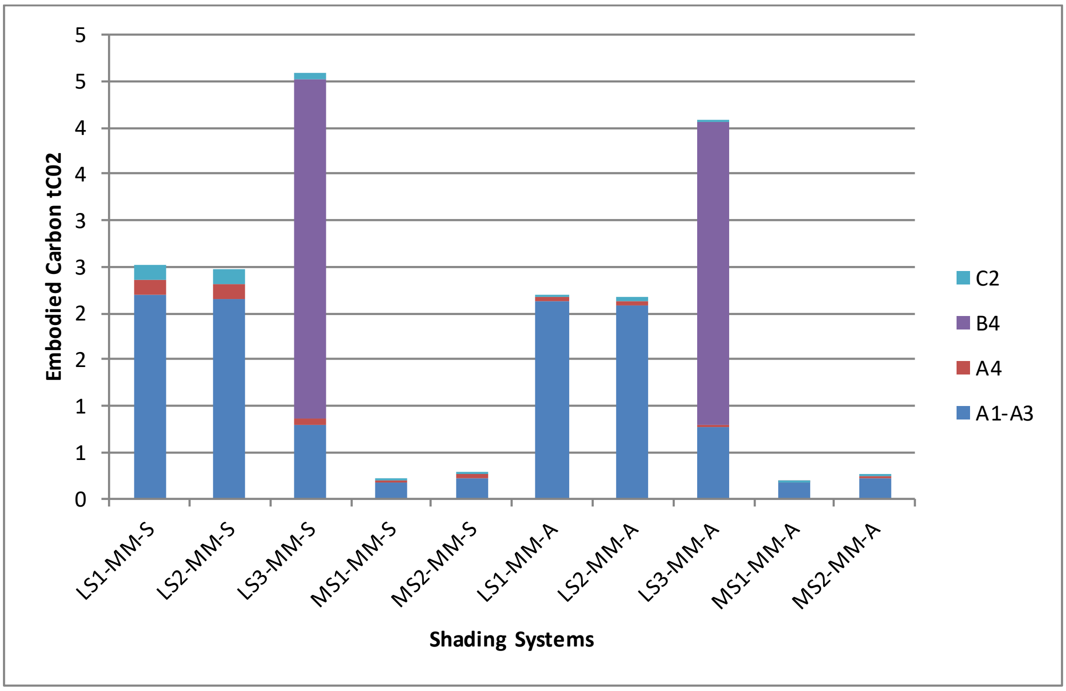


Figure 10: Embodied energy average values for all the shading systems considered (top) and the breakdown of EE for different life cycle stages as a percentage of the whole-life EE (bottom)

For LS3, the impact of the product stage A1-A3 is significant, which influences greatly the high replacement factor B4 associated with such retractable systems. The replacement factor for LS3 is responsible for at least 80% of the whole embodied energy utilised, due to the cumulative effect of A1-A3. On the other hand, the louver systems LS1 and LS2 have the highest volume of material used, reflected in the results obtained for the product stage. However, since they are of a more durable nature, this material investment is likely to occur on a one-time basis in a 25-year lifespan. A comparison of the louver and mesh systems highlights the significantly lower embodied energy impacts obtained for the latter. The difference between the louver and mesh systems is noted in the production stage, A1-A3. In both mesh systems, the initial material investment is low when compared to the other devices studied. Furthermore, in all the systems considered, transportation was not a significant factor. This result is consistent with findings from other studies [51], [55].



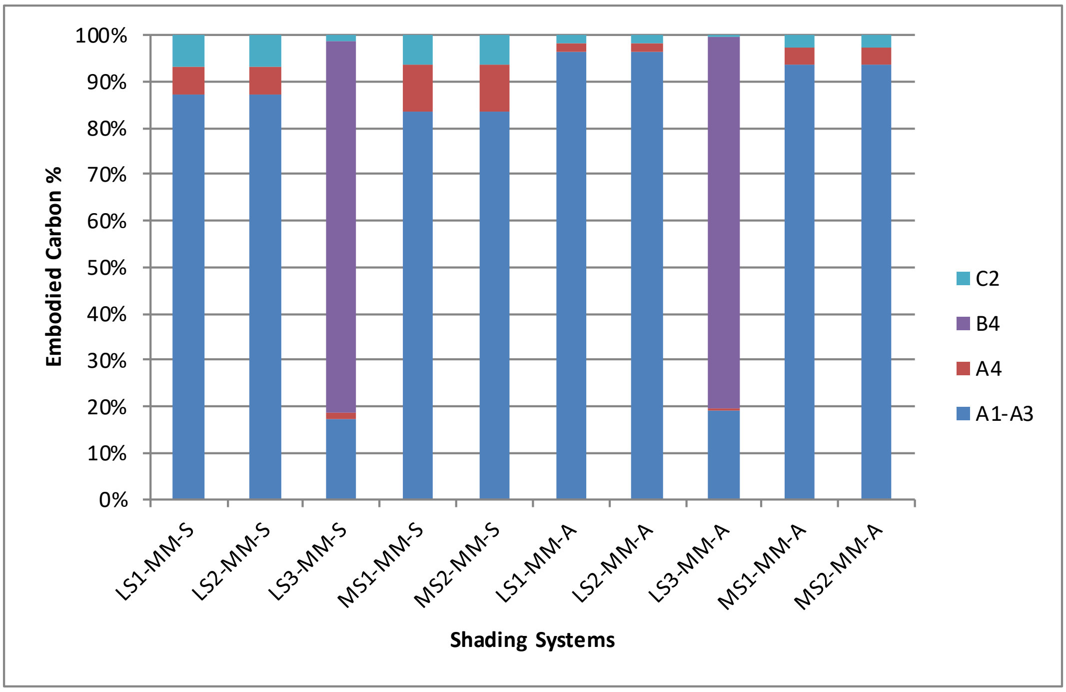


Figure 11: Embodied carbon average values for all the shading systems considered (top) and the breakdown of EC for different life cycle stages as a percentage of the whole-life EC (bottom)

Figure 11 presents the average values of the embodied carbon calculated for each shading system. Similarly to the results obtained for the EE impacts, the highest EC was noted for LS3. The remaining louver systems performed similarly to each other; however the lowest EC impact was reported for the mesh systems with MS1 reporting the lowest embodied carbon. Similarly to the EE results, this favourable performance may be attributed to the lower mass of the mesh systems. In contrast to the EE results, the impact of the steel systems with regards to EC was higher than the aluminium systems EC impact. In fact, all steel systems resulted in an EC increase of circa 12-15%.

4.5 Whole-life energy and carbon balances

From Figure 12, it is clear that from all the shading systems considered, the only ones that provide an energy and carbon savings from a whole life perspective are the mesh systems. These savings are brought about by the low EE&C used due to the low weight associated with these systems, as well as a significant reduction in the OE consumed. The largest gains were noted for the LS3 systems and the remaining shading systems all resulted in both an energy and carbon increase.

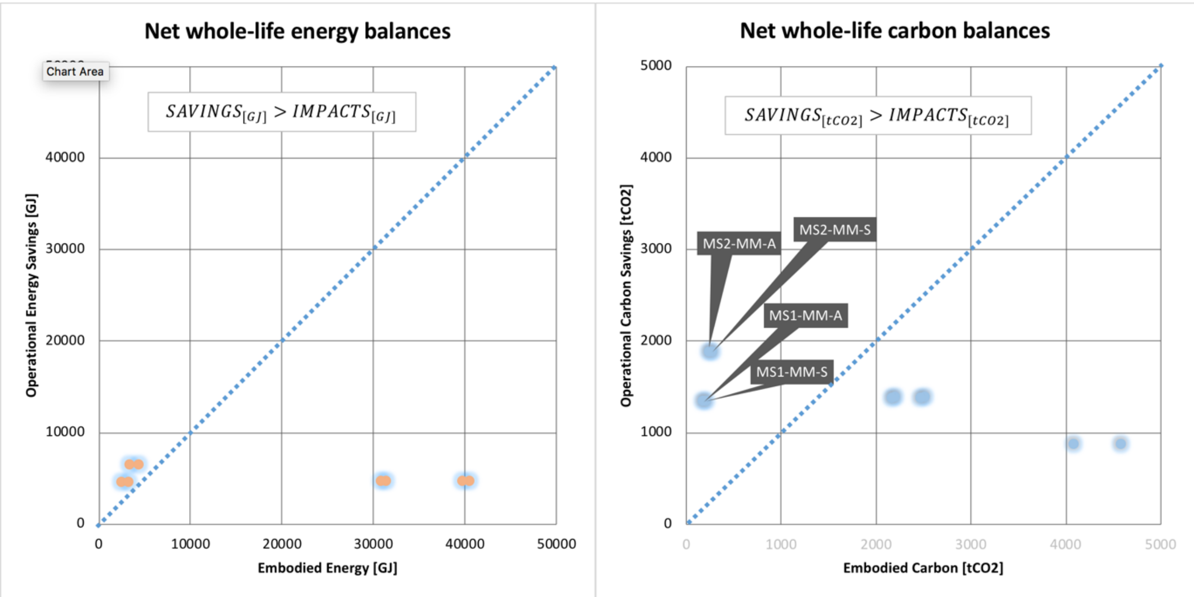


Figure 12: Net whole-life energy (left) and carbon (right) balances

The left-hand side of Figure 12 shows results for energy and the right-end side for carbon. Points in the upper-left half of the charts are representatives of configurations where the savings outweigh the embodied impacts. In other words, the embodied 'costs' incurred to realise those solutions are more than compensated by the energy and carbon savings that those solutions achieve. It is worth noting that these results are likely to hold even with the inclusion of the life cycle stages currently omitted from this study. Indeed, even if the embodied impacts doubled for those configurations, the points would still fall within the area of the graph where operational savings outweigh embodied impacts.

5 Discussion

The results have shown that with louvers and meshes on the South Façade of an office block in Malta, a decrease in internal temperature could be achieved. By studying the predicted mean vote for comfort obtained for each system under a natural ventilation strategy, it was evident that the systems, LS1, LS2, and MS2 provided a comfortable environment for 60% of the time. MS1 provided a comfortable environment for 55% and LS3 reported a comfortable environment range for 46% of the time, while the base case achieved only 40%. By also analysing the uncomfortable region, it became clear that MS2, a wire mesh with an openable area of 25%, had the lowest overheating range, leading it to perform the best among the other shading devices considered.

The same pattern in the results was also observed under a mixed mode strategy. The operational energy and carbon required purely for cooling purposes, was calculated over a 25-year life span. These values were based on the cooling loads required, simulated through IES-VE. When compared to the base case system, LS3 reduced OE by 20%, whilst the louvers system LS1 and LS2 reported an OE savings of nearly 31%. Similarly, MS1 also resulted in a 31% decrease. However, the use of MS2 led to a reduction in OE use of 43%. In addition, OC reduced by 40% for MS2, and around 29% for LS1, LS2 and MS1. Similar to the OE results, LS3 achieved an OC reduction of only 18%. No difference was noted between steel systems and aluminium systems in terms of OE&C.

From a life cycle perspective, the retractable louver system, LS3 reported the highest EE&C for both steel and aluminium systems. These high impact values are due to the high replacement factor associated with the base case system. The remaining louver systems LS1 and LS2 reported nearly identical results. In addition, the EE&C for the mesh systems was nearly half of that obtained for the louver systems with MS2 achieving the lowest impact. The main crucial differing factor between the louvers and meshes was the increased volume of material required to produce the louver systems. These findings continue to suggest that the mesh systems are the most promising from the shading systems considered. Overall, higher EE values were noted for aluminium systems, whilst higher EC values were reported for the steel systems due to the carbon intensity of the energy inputs used in the production of the two materials. The OE&C savings were then compared to the EE&C each shading system generated during its life cycle. Only the mesh systems led to an energy and carbon saving, with the largest energy and carbon savings achieved by MS2, the mesh system with an openness factor of 25%.

6 Conclusions

This article investigated the use of alternative passive shading systems to lower cooling loads in non-domestic buildings in the Mediterranean region. Starting from a real building used as a case study, both louvers and meshes, in different configurations, have been modelled and analysed from a life cycle perspective in the context of Malta, taking into account both operational and embodied figures as well as thermal comfort to ensure the creation of an indoor environment able to meet users' needs.

This study is the first of its kind in the Maltese context, which experiences severe hot weather in the summer months that in turn creates high cooling loads in buildings. The findings of this research shed light on shading systems for passive cooling in the Mediterranean region, with the aim to help countries such Malta to design its buildings effectively and work towards meeting its carbon reduction targets. Results have shown that while both louvers and meshes are able to create comfortable indoor environments in some configurations, things change significantly when a whole-life approach is adopted to evaluate net energy and carbon balances, with only mesh systems producing actual savings across the life cycle. Specifically, the fact that all louver systems resulted in a net increase of the whole-life carbon emissions is a concerning finding that should also be evaluated and analysed in other warm climates where they are used as a passive cooling system.

The risk of interventions aimed at reducing operational energy with high embodied energy costs is indeed doubly worrying. Firstly, the whole-life energy and carbon balance still result in actual increases of energy and carbon (meaning that a do-nothing scenario would be likely to cause less harm). Secondly, embodied energy and carbon mostly occur due to activities taking place in the present and short-term future, whereas operational energy savings avoid impacts incurred mostly over the medium/long-term future when the energy grid is likely to be far less-carbon intensive than it is today. Therefore, detailed LCA studies should be carried out on shading systems, rather than assuming that any system will have a positive impact on whole-life energy.

The major limitation of this study is related to the well-known lack of data for LCAs of buildings. This is exacerbated in the contexts of small countries like Malta, where only few studies have been conducted and therefore local data hardly exist. Therefore generic data from the UK has been used for embodied energy coefficients, with local carbon conversion factors applied. In addition, due to lack of detailed and accurate data, some end of life impacts have not been included in the analysis; however this would be unlikely to change results significantly according to values found in the literature. Furthermore, the users' control over the louvers installed in the case study building could not be monitored and modelled although it could influence the performance of the shading system. Therefore, more information is needed on durability and performance and on environmental impacts of building materials. As more data become available, results can be refined and made more context-specific. Additional avenues for future works include the evaluation of how different materials would impact the overall energy demand of buildings in the Maltese context.

References

[1] EC, Roadmap to a Resource Efficient Europe - Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions COM(2011) 571 final. 2011.

[2] BRO, "Building Regulating Office. Ministry for Transport and Infrastructure - NEARLY-ZERO ENERGY BUILDINGS PLAN FOR MALTA," 2015.

[3] Eurostat, "Total greenhouse gas emissions by countries," 2016. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/File:Total_greenhouse_gas_emissions_by_countries_(including_international_aviation_and_indirect_CO2,_excluding_LULUCF),_1990_-_2014_(million_tonnes_of_CO2_equivalents)_updated.png. [Accessed: 08-Apr-2019].

[4] The Energy and Water Agency, "Malta's annual monitoring report for 2017 under Article 24(1) of 'Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC,'" 2017.

[5] European Commission, "COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS An EU Strategy on Heating and Cooling," 2016.

[6] EU, "Directive (EU) 2018/ of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency," Official Journal of the European Union, p. 17, 2018.

[7] U. Stritih, V. V. Tyagi, R. Stropnik, H. Paksoy, F. Haghighat, and M. M. Joybari, “Integration of passive PCM technologies for net-zero energy buildings,” Sustainable cities and society, vol. 41, pp. 286–295, 2018.
[8] X. Sun, Z. Gou, and S. S.-Y. Lau, “Cost-effectiveness of active and passive design strategies for existing building retrofits in tropical climate: Case study of a zero energy building,” Journal of cleaner production, vol. 183, pp. 35–45, 2018.
[9] S. N. Al-Saadi and A. K. Shaaban, “Zero energy building (ZEB) in a cooling dominated climate of Oman: Design and energy performance analysis,” Renewable and Sustainable Energy Reviews, vol. 112, pp. 299–316, 2019.
[10] G. Kim, H. S. Lim, T. S. Lim, L. Schaefer, and J. T. Kim, “Comparative advantage of an exterior shading device in thermal performance for residential buildings,” Energy and buildings, vol. 46, pp. 105–111, 2012.
[11] K. Voss, S. Herkel, J. Pfafferott, G. Löhnert, and A. Wagner, “Energy efficient office buildings with passive cooling–Results and experiences from a research and demonstration programme,” Solar Energy, vol. 81, no. 3, pp. 424–434, 2007.
[12] B. Givoni, Passive Low Energy Cooling of Buildings. John Wiley & Sons, 1994.
[13] R. V. Ralegaonkar and R. Gupta, “Review of intelligent building construction: A passive solar architecture approach,” Renewable and Sustainable Energy Reviews, vol. 14, no. 8, pp. 2238–2242, 2010.
[14] F. Pomponi, P. A. E. Piroozfar, and E. R. P. Farr, “An Investigation into GHG and non-GHG Impacts of Double Skin Façades in Office Refurbishments,” Journal of Industrial Ecology, vol. 20, no. 2, pp. 234–248, 2016.
[15] M. K. Dixit, J. L. Fernández-Solís, S. Lavy, and C. H. Culp, “Identification of parameters for embodied energy measurement: A literature review,” Energy and Buildings, vol. 42, no. 8, pp. 1238–1247, 2010.
[16] A. M. Moncaster and K. E. Symons, “A method and tool for ‘cradle to grave’ embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards,” Energy and Buildings, vol. 66, pp. 514–523, 2013.
[17] G. P. Hammond and C. I. Jones, “Embodied energy and carbon in construction materials,” Proceedings of the ICE - Energy, vol. 161, pp. 87–98, 2008.
[18] S. Stevanović, “Optimization of passive solar design strategies: A review,” Renewable and Sustainable Energy Reviews, vol. 25, pp. 177–196, 2013.
[19] A. A. Y. Freewan, “Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions,” Solar Energy, vol. 102, pp. 14–30, 2014.
[20] A. I. Palmero-Marrero and A. C. Oliveira, “Effect of louver shading devices on building energy requirements,” Applied Energy, vol. 87, no. 6, pp. 2040–2049, 2010.
[21] H. H. Alzoubi and A. H. Al-Zoubi, “Assessment of building fa??ade performance in terms of daylighting and the associated energy consumption in architectural spaces: Vertical and horizontal shading devices for southern exposure facades,” Energy Conversion and Management, vol. 51, no. 8, pp. 1592–1599, 2010.
[22] J. F. Nicol and M. A. Humphreys, “Adaptive thermal comfort and sustainable thermal standards for buildings,” Energy and Buildings, vol. 34, no. 6, pp. 563–572, 2002.
[23] A. G. Mainini, T. Poli, M. Zinzi, and A. Speroni, “Metal mesh as shading devices and thermal response of an office building: parametric analysis,” Energy Procedia, vol. 78, pp. 103–109, 2015.
[24] A. G. Mainini, T. Poli, M. Zinzi, and A. Speroni, “Spectral light transmission measure of metal screens for glass façades and assessment of their shading potential,” Energy Procedia, vol. 48, pp. 1292–1301, 2014.
[25] D. Appelfeld, A. McNeil, and S. Svendsen, “An hourly based performance comparison of an integrated micro-structural perforated shading screen with standard shading systems,” Energy and Buildings, vol. 50, pp. 166–176, 2012.

[26] A. Sherif, A. El-Zafarany, and R. Arafa, “External perforated window Solar Screens: The effect of screen depth and perforation ratio on energy performance in extreme desert environments,” Energy and Buildings, vol. 52, pp. 1–10, 2012.
[27] S. Hoffmann and E. Lee, “Potential energy savings with exterior shades in large office buildings and the impact of discomfort glare,” 2015.
[28] F. Hammad and B. Abu-Hijleh, “The energy savings potential of using dynamic external louvers in an office building,” Energy and Buildings, vol. 42, no. 10, pp. 1888–1895, 2010.
[29] T. Ibn-Mohammed, R. Greenough, S. Taylor, L. Ozawa-Meida, and A. Acquaye, “Operational vs. embodied emissions in buildings—A review of current trends,” Energy and Buildings, vol. 66, no. 0, pp. 232–245, 2013.
[30] F. Pomponi and A. M. Moncaster, “Embodied carbon mitigation and reduction in the built environment – What does the evidence say?,” J Environ Manage, vol. 181, pp. 687–700, 2016.
[31] F. Pomponi and A. M. Moncaster, “Scrutinising embodied carbon in buildings: the next performance gap made manifest,” Renewable & Sustainable Energy Reviews, vol. 81, no. 2, pp. 2431–2442, 2018.
[32] F. Pomponi, A. Moncaster, and C. De Wolf, “Furthering embodied carbon assessment in practice: Results of an industry-academia collaborative research project,” Energy and Buildings, vol. 167, pp. 177–186, 2018.
[33] A. M. Moncaster, F. Pomponi, K. E. Symons, and P. M. Guthrie, “Why method matters: Temporal, spatial and physical variations in LCA and their impact on choice of structural system,” Energy and Buildings, vol. 173, pp. 389–398, 2018.
[34] F. Pomponi and L. M. Campos, “Embodied and Life Cycle Carbon Assessment of Buildings in Latin America: State-of-the-Art and Future Directions,” in Embodied Carbon in Buildings, Springer, 2018, pp. 483–503.
[35] BSI, “BS EN 15978:2011. Sustainability of construction works — Assessment of environmental performance of buildings — Calculation method,” 2011.
[36] BS, “BS EN 15643-2:2011. Sustainability of construction works — Sustainability assessment of buildings. Part 2: Framework for the assessment of environmental performance,” 2011.
[37] T. Ramesh, R. Prakash, and K. K. Shukla, “Life cycle energy analysis of buildings: An overview,” Energy and Buildings, vol. 42, no. 10, pp. 1592–1600, 2010.
[38] Y. Huang, J. Niu, and T. Chung, “Energy and carbon emission payback analysis for energy-efficient retrofitting in buildings—Overhang shading option,” Energy and Buildings, vol. 44, pp. 94–103, 2012.
[39] F. Stazi, S. Marinelli, C. Di Perna, and P. Munafò, “Comparison on solar shadings: Monitoring of the thermo-physical behaviour, assessment of the energy saving, thermal comfort, natural lighting and environmental impact,” Solar Energy, vol. 105, pp. 512–528, 2014.
[40] H. Babaizadeh, N. Haghighi, S. Asadi, R. Broun, and D. Riley, “Life cycle assessment of exterior window shadings in residential buildings in different climate zones,” Building and Environment, vol. 90, pp. 168–177, 2015.
[41] R. K. Yin, Case study research: Design and methods, 4th ed. Thousands Oak, CA: Sage publications, 2009.
[42] D. Proverbs and R. Gameson, “Case study research,” Advanced research methods in the built environment, pp. 99–110, 2008.
[43] R. Azari, “Integrated energy and environmental life cycle assessment of office building envelopes,” Energy and Buildings, vol. 82, pp. 156–162, 2014.
[44] Haver & Boecker, “Doka-Mono 1601. Available at: http://www.weavingarchitecture.com/en/architectural-mesh-types/wire-mesh/doka-mono/1601/ [Accessed June 16, 2016].,” 2014. .
[45] Haver & Boecker, “Largo-Plenus 2022. Available at: http://www.weavingarchitecture.com/en/architectural-mesh-types/wire-mesh/largo-plenus/2022/ [Accessed June 26, 2016].,” 2014. .

[46] F. Pomponi, “Operational Performance and Life Cycle Assessment of Double Skin Façades for Office Refurbishments in the UK,” University of Brighton, United Kingdom (UK), 2015.
[47] BSI, “BS EN 15251:2007 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.,” ISBN 978 0 580 50806 6, 2007.
[48] CIBSE, “TM 52: 2013 - The limits of thermal comfort: avoiding overheating in European buildings,” Great Britain, 2013.
[49] CIBSE, “Building energy and environmental modelling. CIBSE Applications Manual AM11:1998.,” © April 1998 The Chartered Institution of Building Services Engineers London (reprinted 2010), 2010.
[50] E. Gavotsis and A. Moncaster, “Practical limitations in Embodied Energy and Carbon measurements, and how to address them: a UK case study,” 2014.
[51] F. Pomponi, P. A. E. Piroozfar, R. Southall, P. Ashton, and E. R. P. Farr, “Life cycle energy and carbon assessment of double skin façades for office refurbishments,” Energy and Buildings, vol. 109, pp. 143–156, 15 2015.
[52] DEFRA and Department for Environment Food & Rural Affairs, 2016 Government GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors. 2013.
[53] IEA, “Statistics | Malta - Total CO2 emissions (chart),” 2016. [Online]. Available: https://www.iea.org/statistics/?country=MALTA&year=2016&category=Emissions&indicator=TotCO2&mode=chart&dataTable=INDICATORS. [Accessed: 08-Apr-2019].
[54] G. Datta, “Effect of fixed horizontal louver shading devices on thermal perfomance of building by TRNSYS simulation,” Renewable energy, vol. 23, no. 3–4, pp. 497–507, 2001.
[55] K.-H. Kim, “A comparative life cycle assessment of a transparent composite facade system and a glass curtain wall system,” Energy and Buildings, vol. 43, no. 12, Dec. 2011.